

# ***Search for Gravitational Waves from Black Hole Ringdowns***

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and the TAMA Collaboration**

# Outline

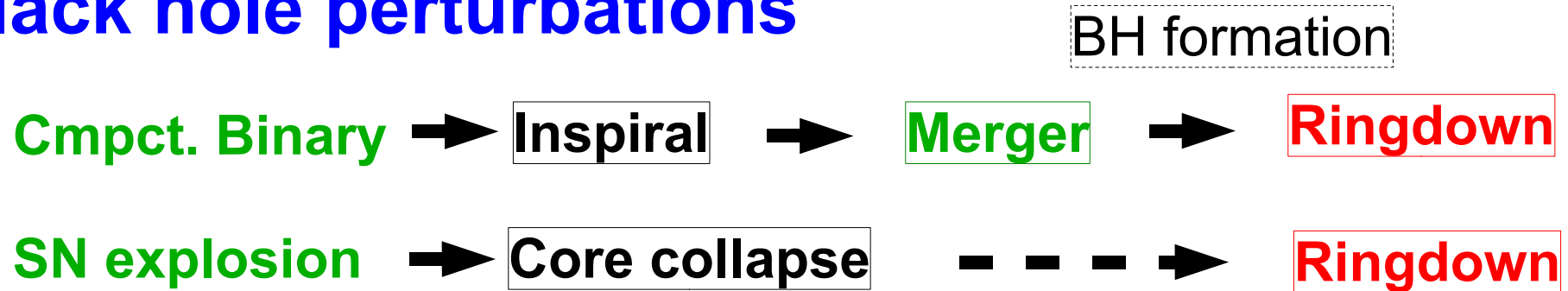


- **Black holes (BHs), quasi-normal modes (QNMs) and ringdowns**
- **TAMA300 sensitivity, signal-to-noise ratios (SNRs)**
- **Matched-filtering, template construction**
- **Detection probability of Galactic ringdown events with TAMA300**
- **Vetoing techniques**
- **Summary**

# BHs, QNMs and Gravitational Waves



- **Black hole perturbations**



**Damped oscillation with QNMs,  
“Ringdown”**

$$h(t) = A \exp(-\pi f_c t / Q) \sin(2\pi f_c t)$$

- **Central frequency**

$$f_c \approx \frac{3.2 \times 10^4}{M} [1 - 0.63(1 - a)^{0.3}] [\text{Hz}]$$

- **Quality factor**

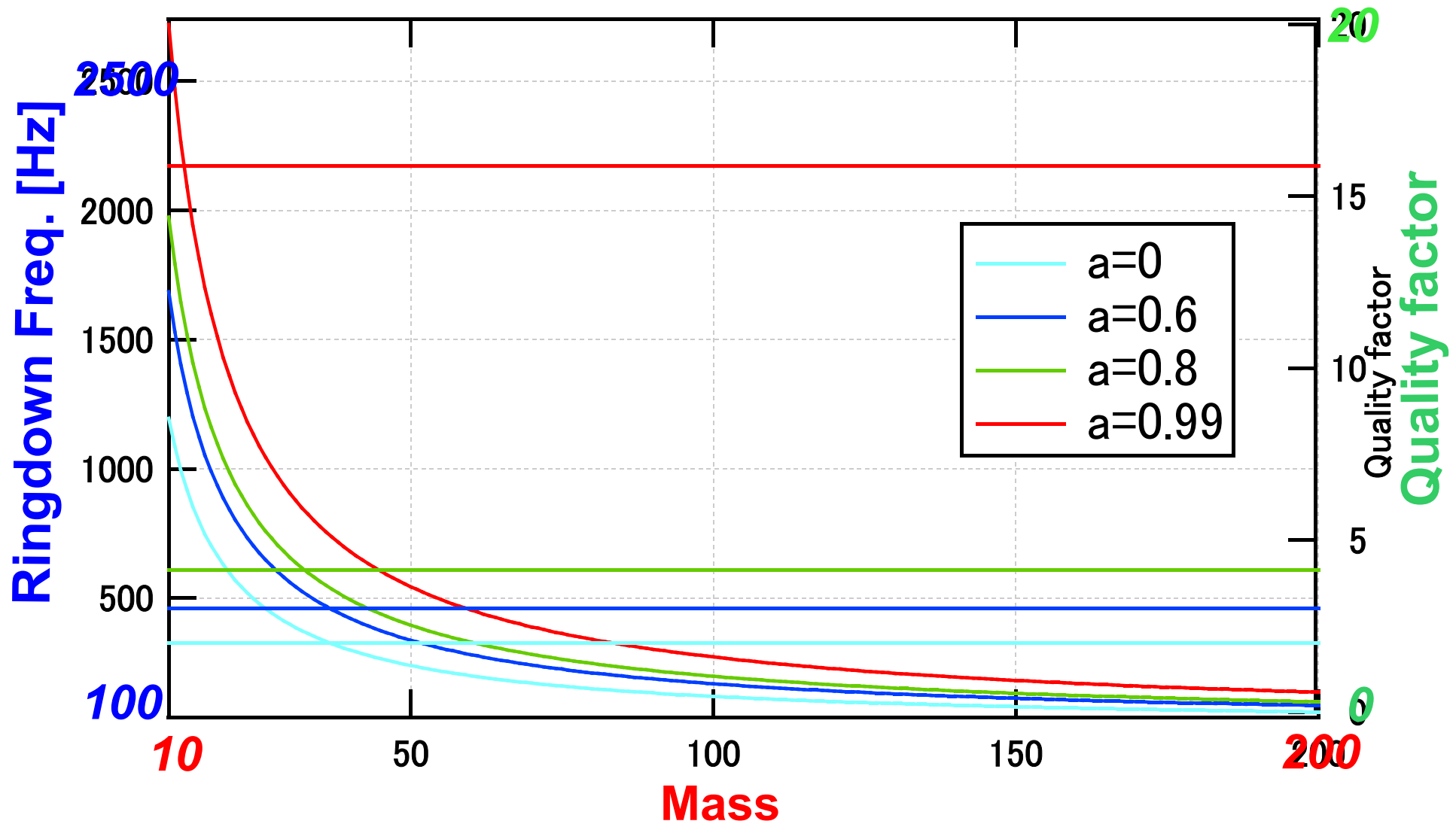
$$Q \approx 2.0 (1 - a)^{-0.45}$$

Echeverria, (1989)

$M$ : BH mass (in solar mass unit)  
 $a$ : Spin angular momentum, (0 - 1)

# $(f_c, Q) - (M, a)$

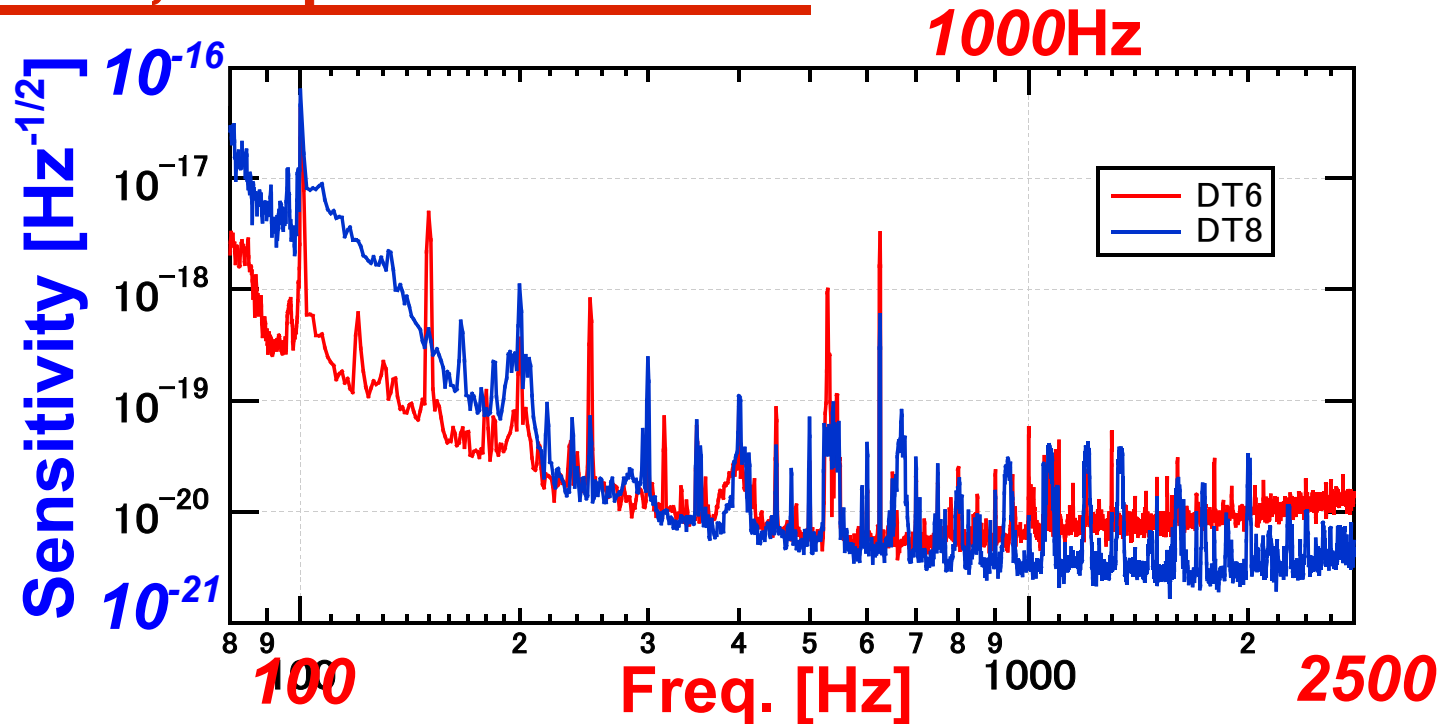
$$f_c \approx \frac{3.2 \times 10^4 [\text{Hz}]}{M} [1 - 0.63(1-a)^{0.3}], \quad Q \approx 2.0(1-a)^{-0.45}$$



# TAMA sensitivities, Expected SNRs

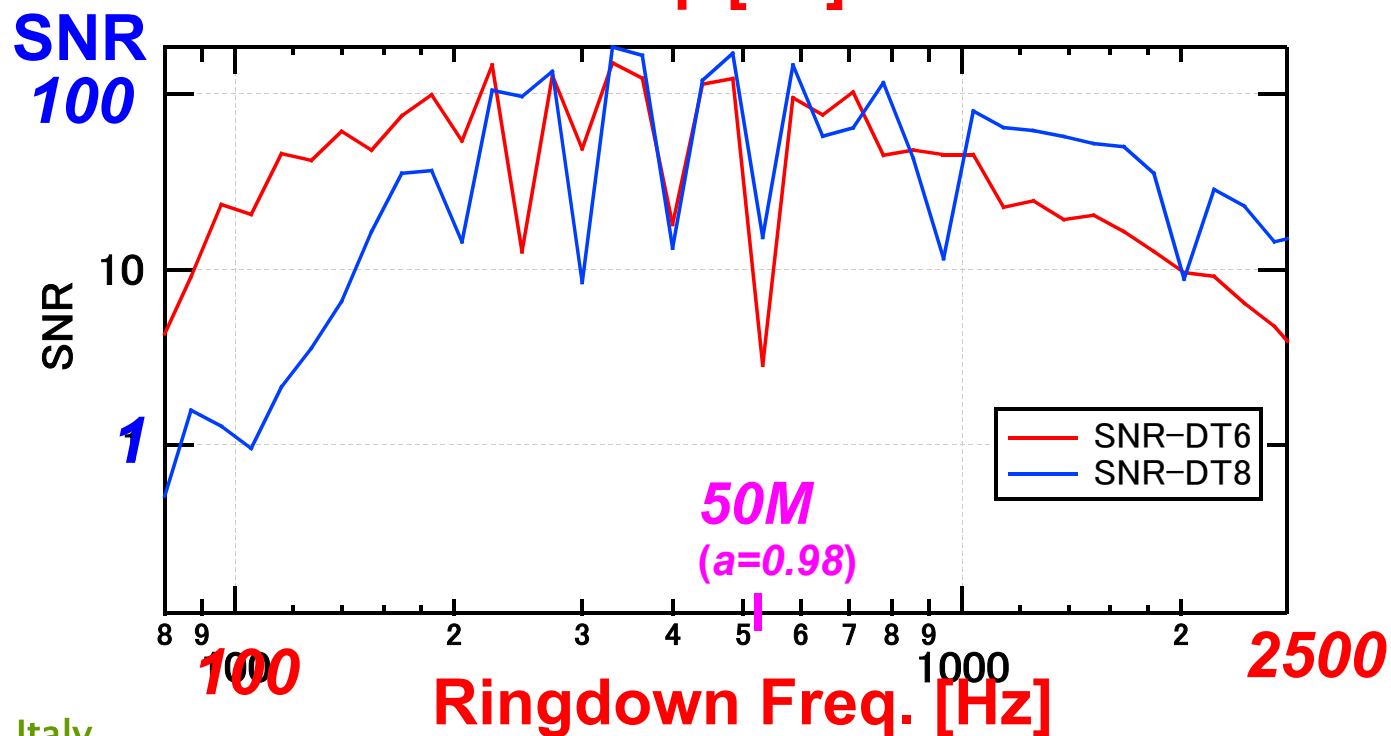


**TAMA300**  
**sensitivities**  
**2001 (DT6)**  
**2003 (DT8)**



**Signal-to-Noise**  
**ratios**

$a = 0.98,$   
 $D = 10$  [kpc]



# Matched-filtering

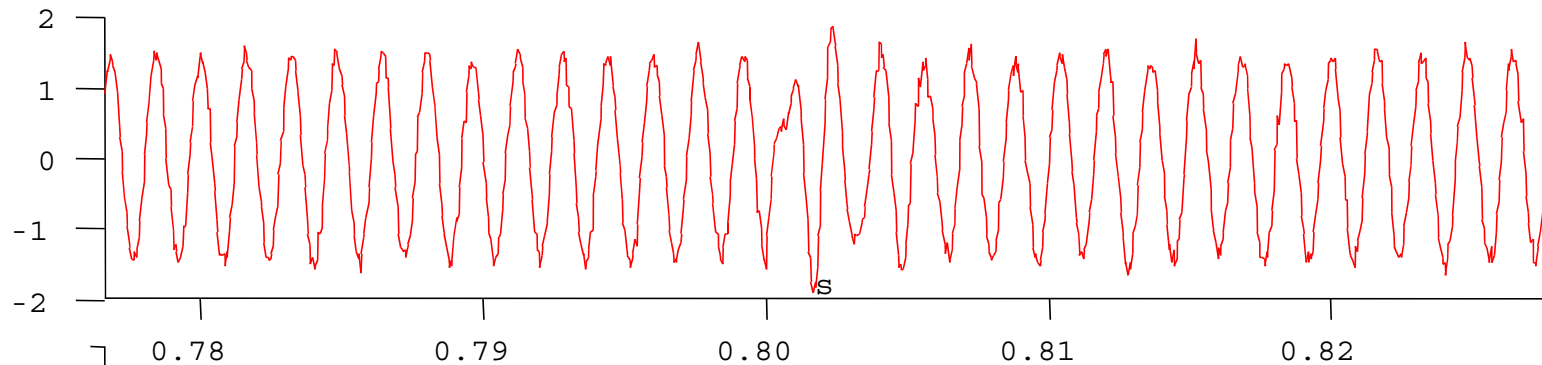
$$\rho = \int \frac{s(f) h^*(f)}{S_n(f)} df$$

**$s(f)$** : Strain data

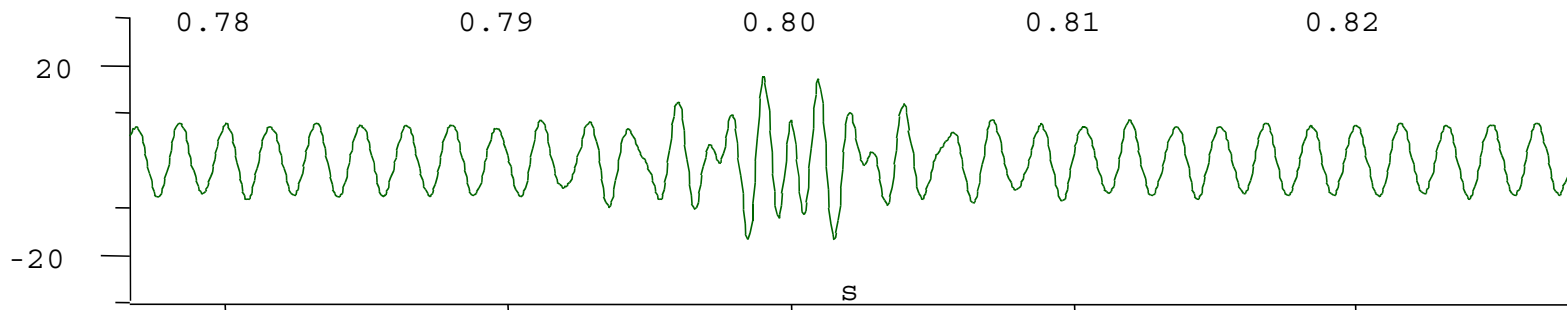
**$h(f)$** : Template

**$S_n(f)$** : Noise power

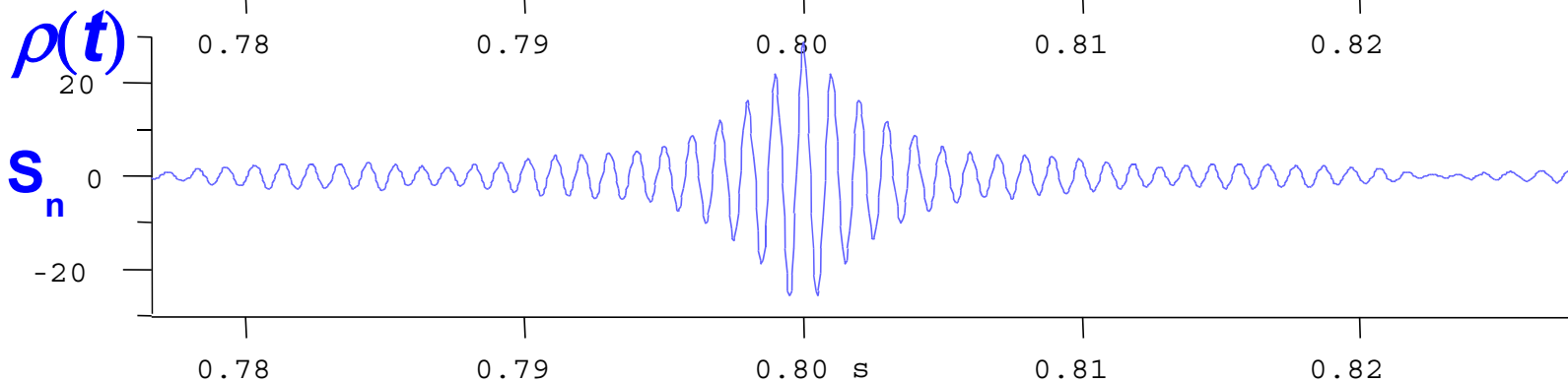
**$s(t)$**   
strain data



**$s(t)+h(t)$**   
(test signal)



**Filter output**  
weighted by  $S_n$



# Template construction

$$\rho = \int \frac{s(f) h^*(f)}{S_n(f)} df \quad h(f) = h(f; \underline{f_c}, Q)$$

- Search range:

$$f_c = 100 \sim 2500 \text{ [Hz]}$$

$$Q = 2 \sim 20$$

- Number of templates:

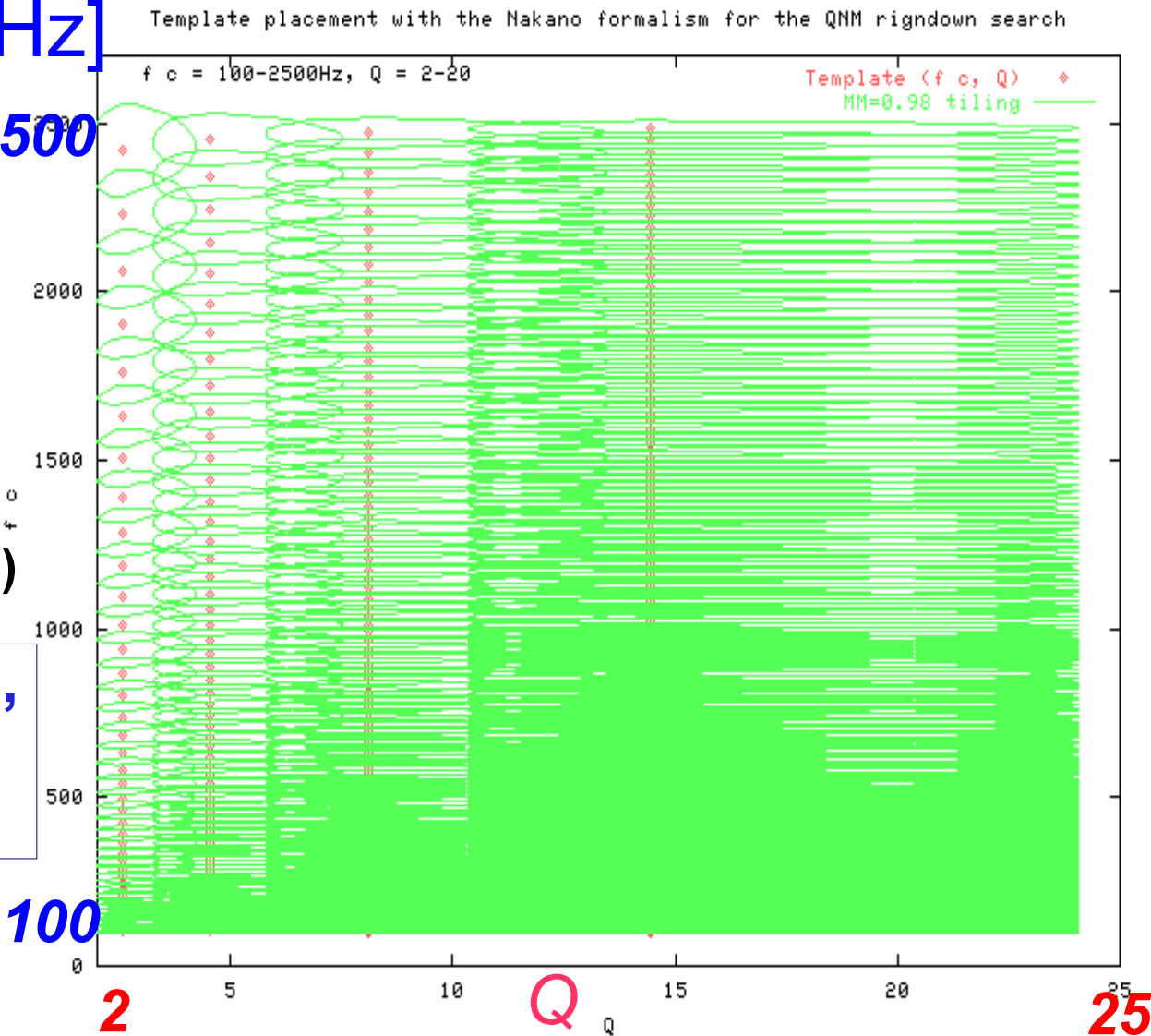
~ 800

for max SNR loss = 2 %  
( Minimal match  $MM = 0.98$  )

Nakano, Takahashi et al.,  
gr-qc/0306082  
(submitted to PRD)

$f_c$  [Hz]

2500



100

2

5

10

Q

15

20

25

# Detection efficiency for Galactic Ringdowns



- **MC simulation** (Signal injection into the TAMA data)

- **Source distribution**  $dN = \exp(-R^2/2R_0^2) \exp(-z/h_z) R dR dz$

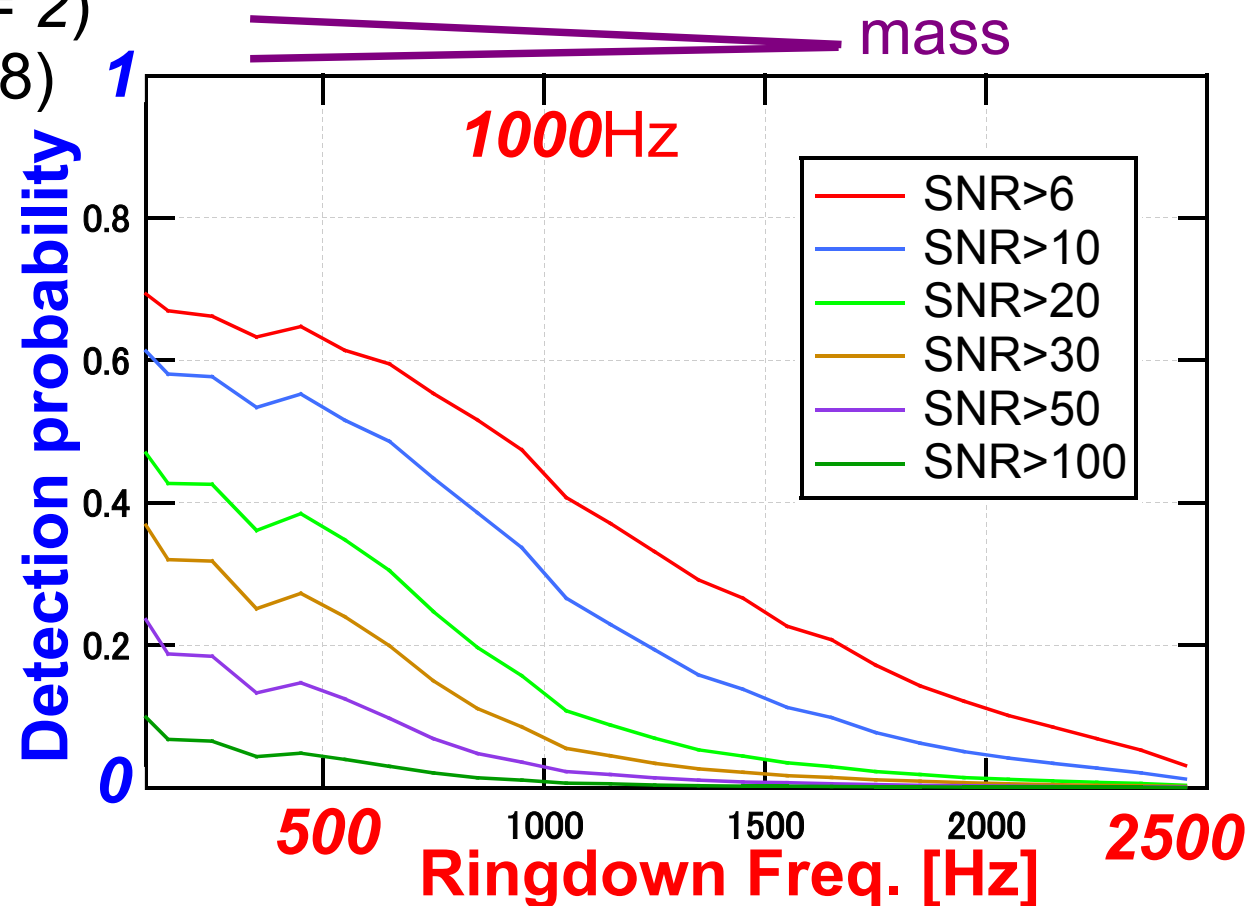
$$R_0 = 4.8 \text{ [kpc]}, h_z = 1 \text{ [kpc]}$$

- $\eta = 0.03$  for fractional mass energy radiated as GWs ( $l = m = 2$ ) (Flanagan & Hughes, 1998)

- **Radiation pattern** (random inclination angle)

- **Observation period, antenna pattern**

- **SNR losses due to template spacing**

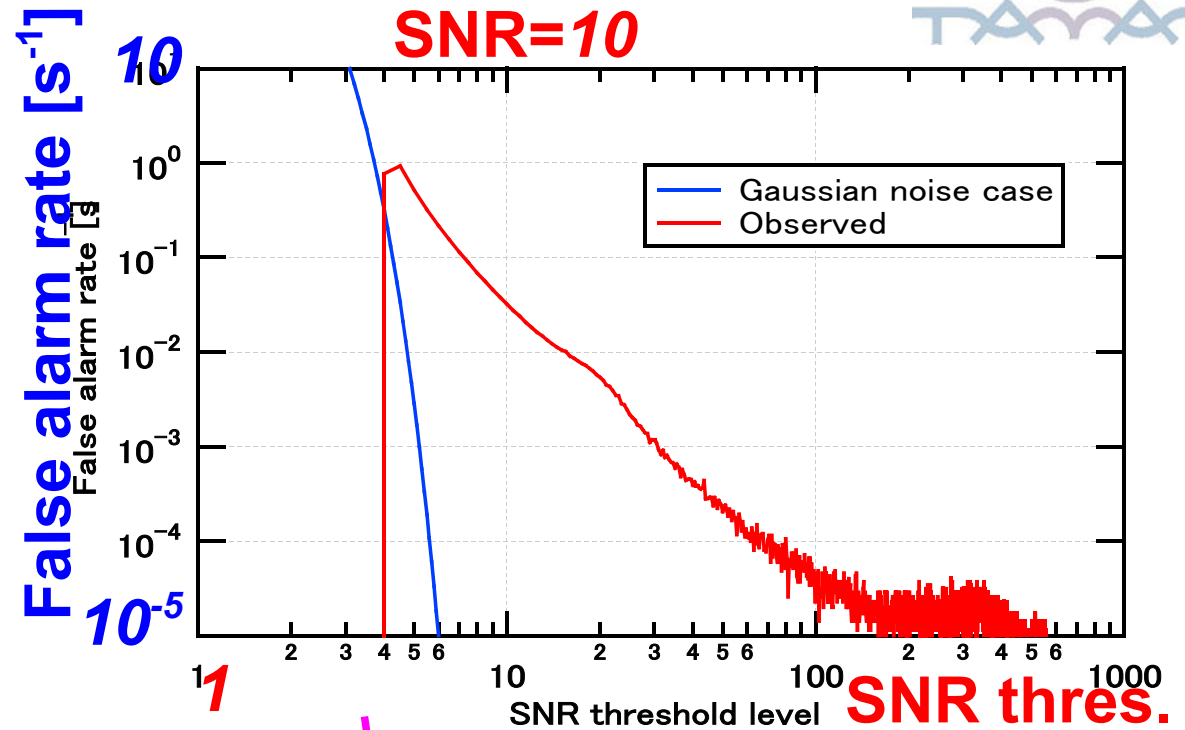


# Filter outputs

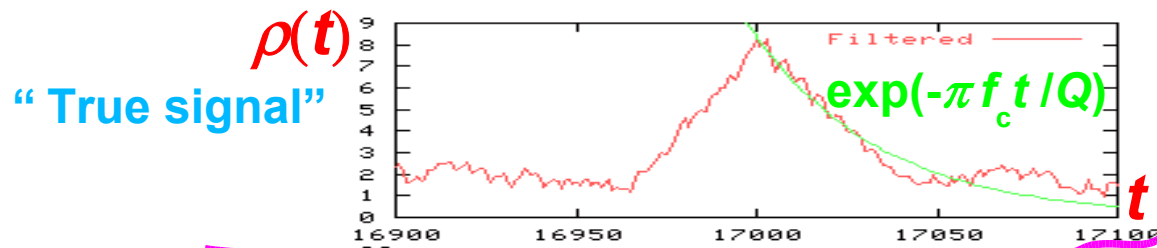
- False alarm rate  
(SNR > 10)

~ 0.03 [s<sup>-1</sup>] (!)

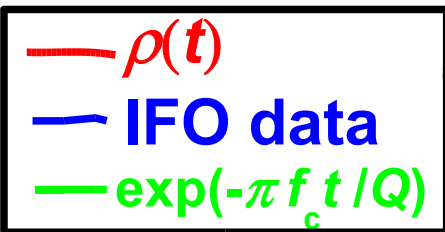
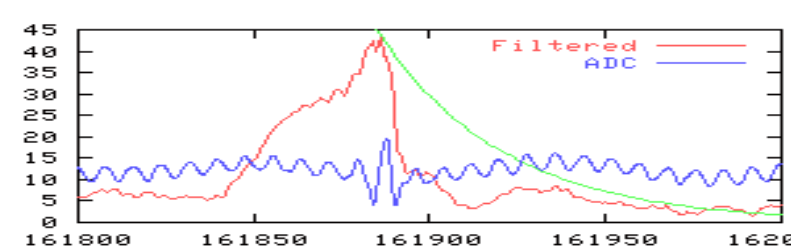
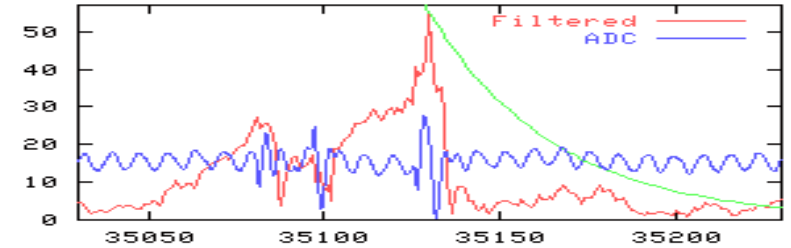
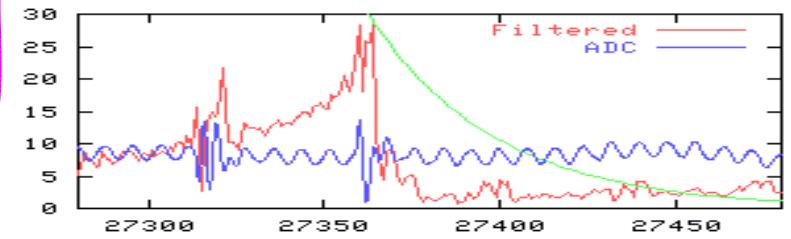
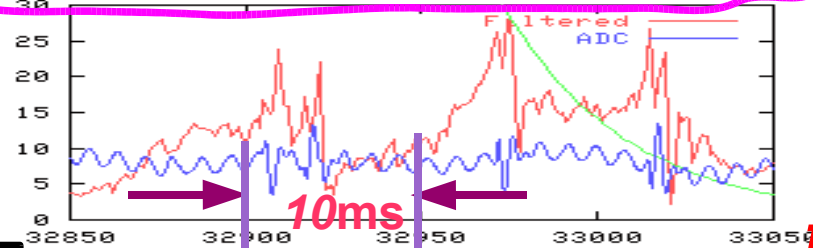
(cf. ~10<sup>-19</sup> [s<sup>-1</sup>]  
for Gaussian noises)



- Event appearance



Spurious events

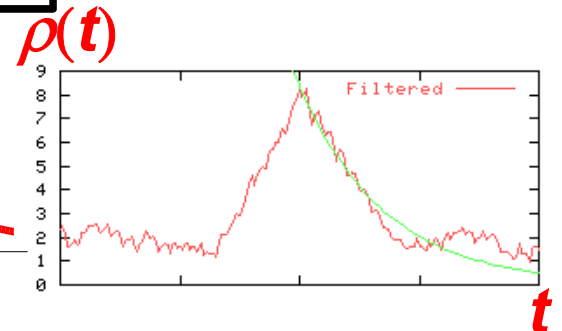
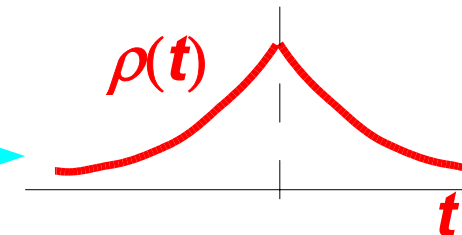
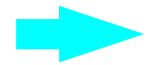
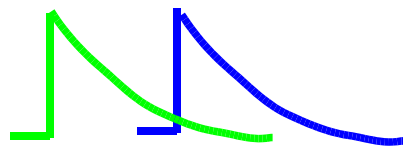


# Vetoing techniques

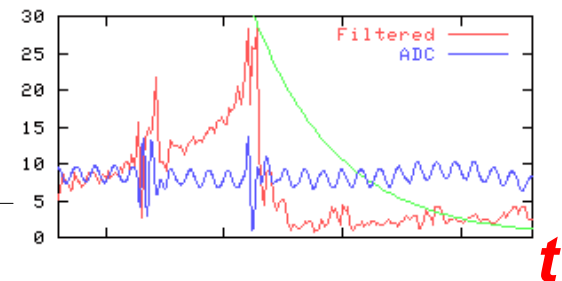
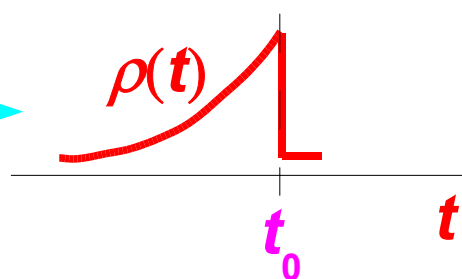
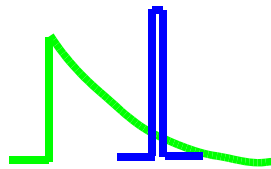
- Characterizing spurious events



“True signal”

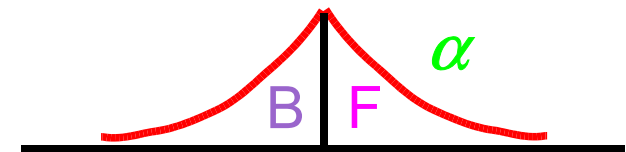


Impulsive noise



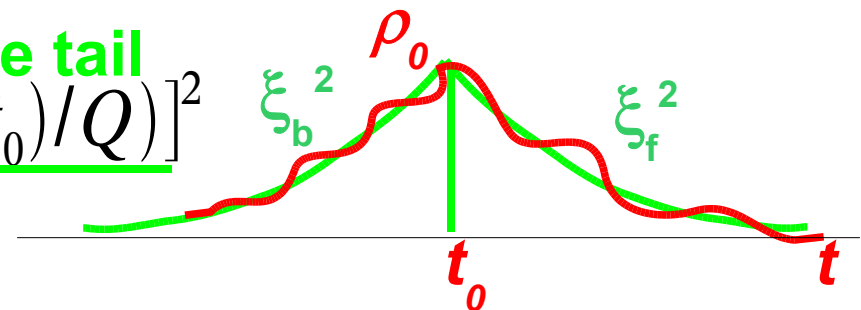
## • Vetoing parameters

- asymmetry,  $\alpha = (F - B) / (F + B)$
- Fit to the exponential tail



$$\xi^2 \equiv \frac{1}{\rho_0} \sum [\rho(t) - \rho_0 \exp(-\pi f_c (t - t_0) / Q)]^2$$

template tail  
Filter output



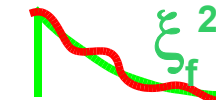
# Vetoing techniques



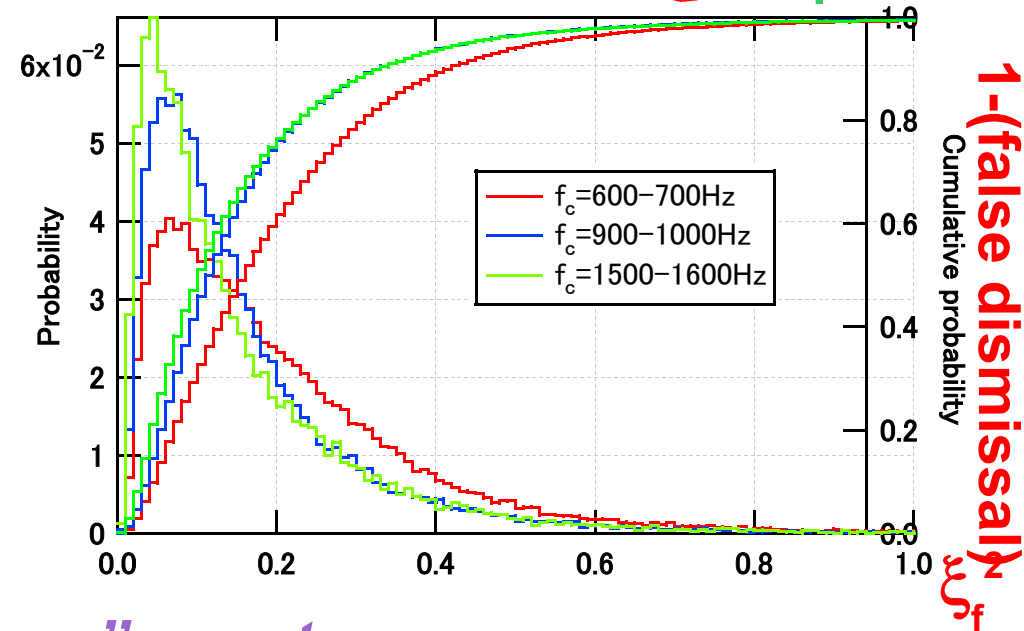
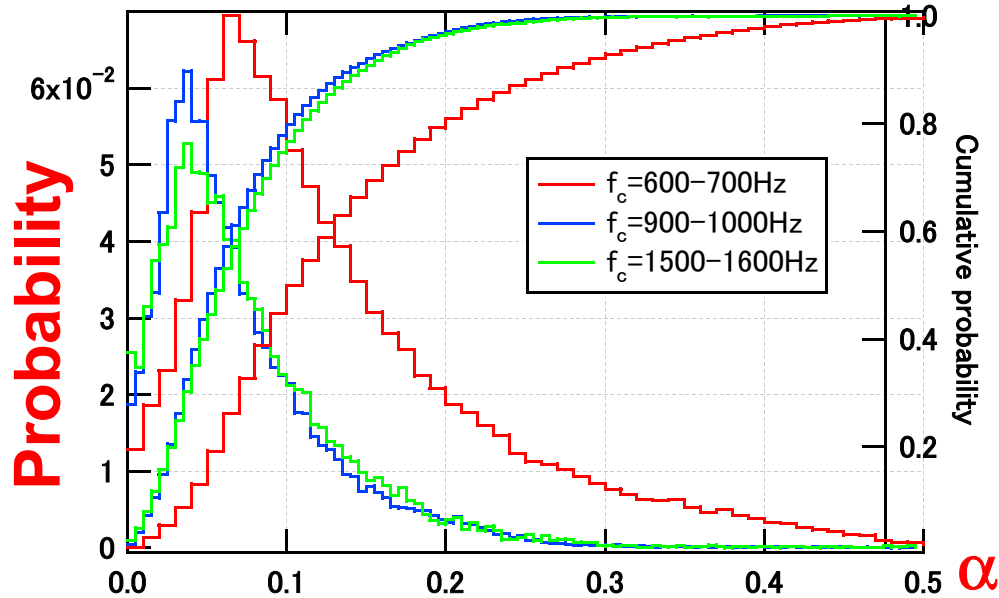
asymmetry



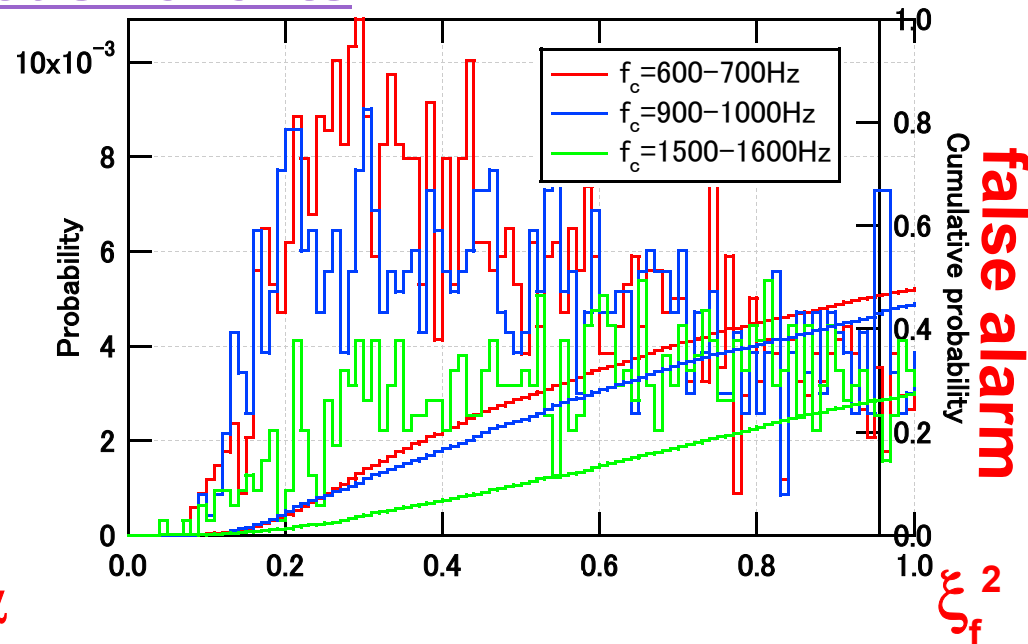
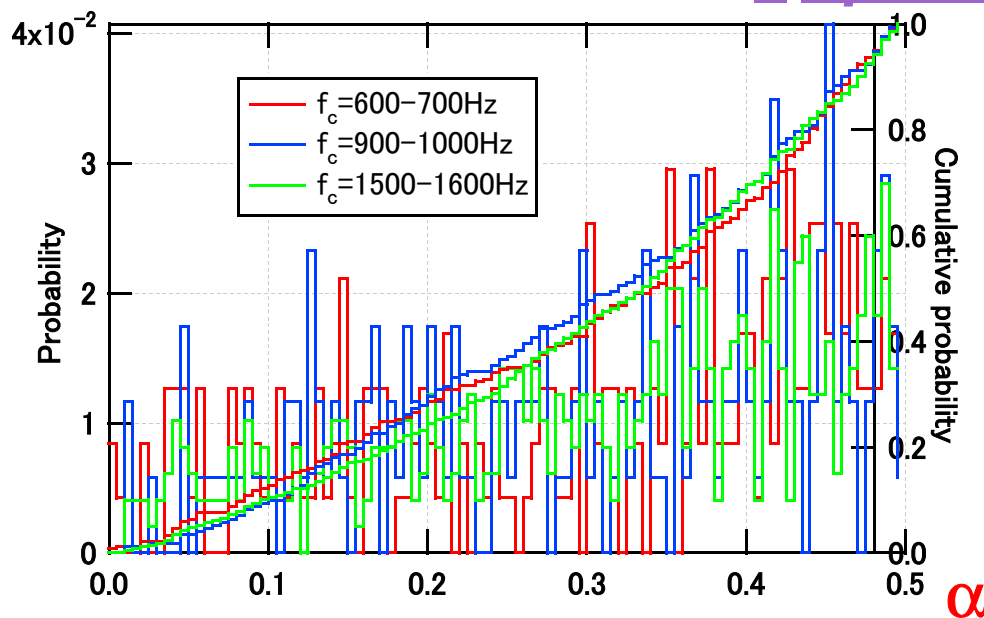
“True” (injected) signal



Fit to the exp tail



“Spurious” events

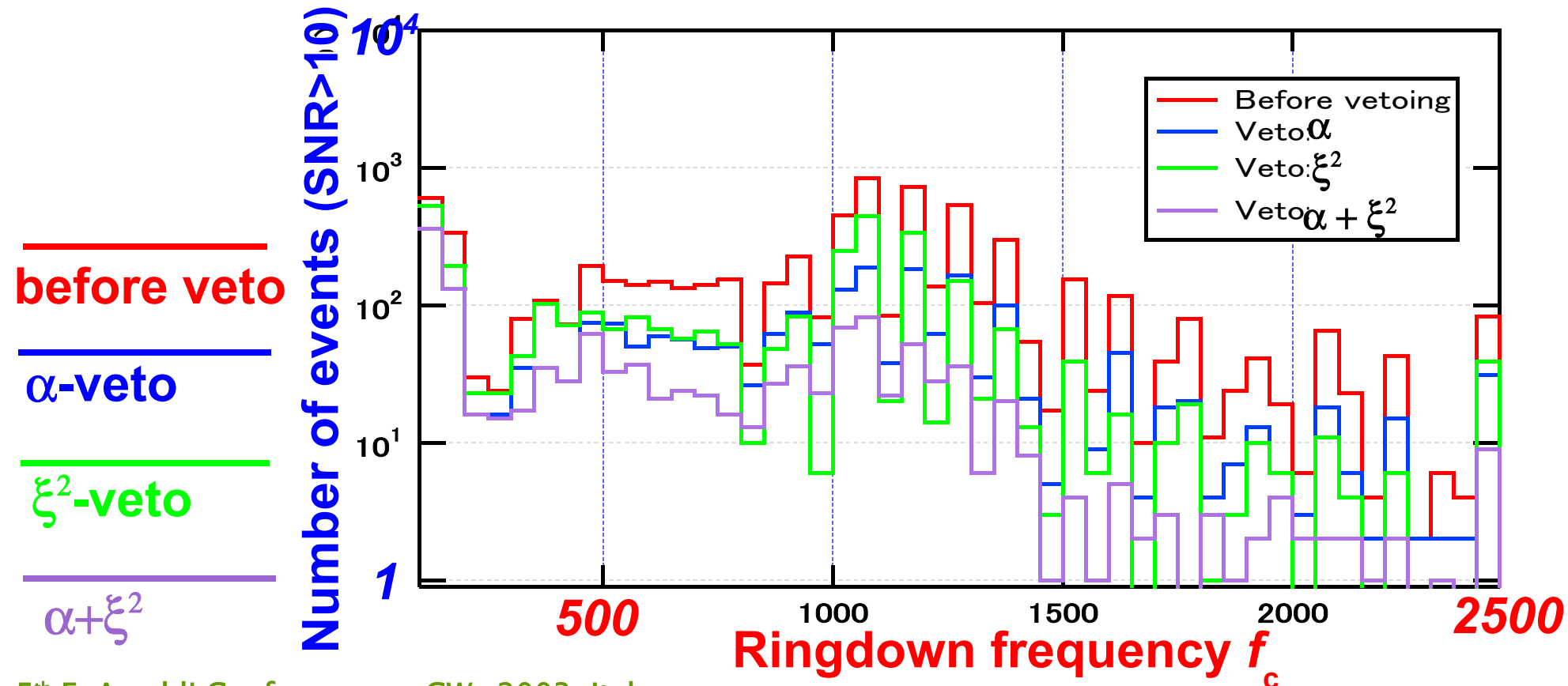


# Veto: Example

- TAMA DT6/R101, ~1 day data

- **Criteria:**

- **SNR > 10**
- **$\alpha$ -veto,  $\xi_f^2$ -veto:** cut so as to be false dismissal 5 %  
(determined from the simulation results)



# Summary



- **BH ringdown GW search with the matched-filtering analysis** DT6 analysis completed, DT8 under progress
- **An efficient template construction method implemented** (Nakano, Takahashi et al. 2003)
- **Ringdown parameters:  $(f_c, Q) = (100 - 2500\text{Hz}, 2 - 20)$ ,  
 $N_{\text{tmplt}} = 800$**
- **Detection efficiency 50 ~ 60% for Galactic ringdown events** (SNR > 10, assuming GW luminosity ~ 3 %)
- **Vetoing by examining asymmetries and exp tails of filter outputs  $\rho(t)$**
- **Rejection power ~ 90% with a false dismissal 5%**
- **... Still a number of fakes ....., more careful investigation required for the event selection**